RECENT RAPID REGIONAL CLIMATE WARMING ON THE ANTARCTIC PENINSULA

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Abstract. The Intergovernmental Panel on Climate Change (IPCC) confirmed that mean global warming was $0.6 \pm 0.2\,°C$ during the 20th century and cited anthropogenic increases in greenhouse gases as the likely cause of temperature rise in the last 50 years. But this mean value conceals the substantial complexity of observed climate change, which is seasonally- and diurnally-biased, decadally-variable and geographically patchy. In particular, over the last 50 years three high-latitude areas have undergone recent rapid regional (RRR) warming, which was substantially more rapid than the global mean. However, each RRR warming occupies a different climatic regime and may have an entirely different underlying cause. We discuss the significance of RRR warming in one area, the Antarctic Peninsula. Here warming was much more rapid than in the rest of Antarctica where it was not significantly different to the global mean. We highlight climate proxies that appear to show that RRR warming on the Antarctic Peninsula is unprecedented over the last two millennia, and so unlikely to be a natural mode of variability. So while the station records do not indicate a ubiquitous polar amplification of global warming, the RRR warming on the Antarctic Peninsula might be a regional amplification of such warming. This, however, remains unproven since we cannot yet be sure what mechanism leads to such an amplification. We discuss several possible candidate mechanisms: changing oceanographic or changing atmospheric circulation, or a regional air-sea-ice feedback amplifying greenhouse warming. We can show that atmospheric warming and reduction in sea-ice duration coincide in a small area on the west of the Antarctic Peninsula, but here we cannot yet distinguish cause and effect. Thus for the present we cannot determine which process is the probable cause of RRR warming on the Antarctic Peninsula and until the mechanism initiating and sustaining the RRR warming is understood, and is convincingly reproduced in climate models, we lack a sound basis for predicting climate change in this region over the coming century.

1. Introduction

The Intergovernmental Panel on Climate Change (Houghton et al., 2001) has determined that *global warming*, the average warming of the surface of the planet, was $0.6 \pm 0.2\,°C$ during the 20th century⋆ and that 'most of the observed warming

⋆ Here we use the terms *global warming* to denote the mean rate of warming of the planet, and *climate change* to denote all changes in all climate variables with time. Following the Intergovernmental Panel on Climate Change, we intend neither term to imply a root cause in natural variability or human activity.

Climatic Change **60:** 243–274, 2003.

over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations'. Moreover, in the past few decades global mean temperature was the highest of any period in the last millennium (Mann et al., 1999). These are impressive headline figures, but they conceal the real complexity of contemporary *climate change*, which is seasonally- and diurnally-biased (Chapman and Walsh, 1993; Horton, 1995), decadally variable (Nicholls et al., 1995) and geographically patchy (Hansen et al., 1999).

In this study we focus on this patchiness and describe one of three areas of *recent rapid regional (RRR) warming*, where the regional changes have been far more profound than the global warming noted by the IPCC. Here we use 'regional', in accordance with IPCC terminology (Giorgi et al., 2001) to imply areas in the range 10^4–10^7 km^2 and we adopt the multi-disciplinary approach recommended in that report to assess our understanding of the significance, and possible mechanisms leading to RRR warming on the Antarctic Peninsula. We investigate how RRR warming on the Antarctic Peninsula relates to continental temperature changes, and by referring to proxy records show that it is unlikely that a similar event has occurred during the last 1800 years, and so this is unlikely to be due simply to a natural mode of variability. We consider evidence of regional feedback processes that might be amplifying natural modes of variability in climate, or amplifying global climate change in this area. Through this discussion we will emphasize that if future climate change, with a projected global mean warming of 1.4–5.8 °C by 2100 (Houghton et al., 2001), shows a similar degree of regional variability over time-scales of ~50-years, we must urgently seek to understand regional climate change in order to develop meaningful adaptation strategies.

2. Recent Rapid Regional Warming

The geographical patchiness of recent climate change is clear in global maps of trends in mean annual air temperature from meteorological stations. In particular, the Second Assessment Report of the IPCC (Nicholls et al., 1995) showed changes between 1955–74 and 1975–94, and a similar assessment of the NASA Goddard Institute for Space Studies, Global Surface Air Temperature database (Hansen et al., 1999) showed trends for the period 1950–2000 (reproduced in modified form for 1950–2001 in Figure 1). Both assessments show broadly the same, regional or sub-continental, areas of rapid atmospheric warming at northern high-latitudes. These areas are; northwestern North America, and an area centered on the Siberian Plateau in NE Asia. In addition, the data collected by Hansen et al. show another region of warming in the Southern Hemisphere, the Antarctic Peninsula and Bellingshausen Sea. In each area, mean annual temperatures warmed by more than 1.5 °C since 1950, compared to a global mean of ~0.5 °C since 1950 (Folland et al., 2001, Figure 2.1). The Third Assessment Report of the IPCC (Folland et al., 2001) used shorter time intervals, and so tended to highlight slightly different geographic areas, but certainly shows that the same three areas warmed rapidly in the period 1976–2000.

In this study, we will refer to these three areas that have shown unusual behaviour over the last 50 years, as showing recent rapid regional (RRR) warming. Although there is published evidence, at least for the northern hemisphere areas, that this RRR warming may be part of a longer trend and for that reason may be even more significant. For example, a 400-year reconstructed temperature record for the Arctic showed that from 1840 to the mid-20th century, the Arctic warmed to the highest temperature it has reached during the past four centuries (Overpeck et al., 1997). In recent times, the strongest warming appears to have been during the winter and spring (Chapman and Walsh, 1993; Serreze et al., 2000). These changes have been explained as a probable response to changing greenhouse gas concentrations, solar irradiance, aerosol loading from volcanic eruptions and changing atmospheric circulation (Overpeck et al., 1997). This analysis suggested that Arctic warming between 1820 and 1920 was primarily due to reduced forcing by volcanic aerosols and increasing insolation but later increasing greenhouse gas concentrations would have played an increasingly dominant role. This conclusion was, however, the result of attempting to ascribe features in the temperature record to likely controls, rather than any mechanistic proof that these variables could drive the same climate variability, or a convincing simulation by a general circulation model.

Similarly, since the late-1940s, mean annual temperatures over northwestern North America, have risen 1–2 °C, (Hansen et al., 1999; Cayan et al., 2001). These rises appear to have been particularly significant in the Canadian Rocky Mountains, where tree-ring- and glacier-based reconstructions indicate that summer and spring temperatures in the last 50 years were higher than any similar period over the last 900 years (Luckman, 1998) and that the climate of the late 20th century was exceptional in the context of the last 1000 to 3000 years (Luckman, 1998).

We should, however, be cautious of the interpretation that RRR warming in the northern high-latitudes is simply a ubiquitous high-latitude amplification to increased greenhouse gas concentrations. Firstly, because meteorological records (available at http://www.giss.nasa.gov/) show that in the two decades prior to the onset of RRR warming in the 1950s the Siberian Plateau experienced pronounced cooling. Secondly, RRR is not ubiquitous across northern high-latitudes – recent changes in Southern Greenland have been quite complex. According to the sparse meteorological records this area suffered slight cooling in recent decades (Chapman and Walsh, 1993; Hanna and Cappelen, 2002). However, the area of the ice sheet showing a melt-signature in passive microwave imagery increased at 4.4% per year between 1979 and 1991, apparently following temperature (Abdalati and Steffen, 1997), and glaciers near the coast of Greenland have been thinning over the period 1993–98 (Krabill et al., 1999).

In summary, during the last 50 years, mean annual air temperature appears to have risen over much of the northern high-latitudes, but there are two areas of RRR

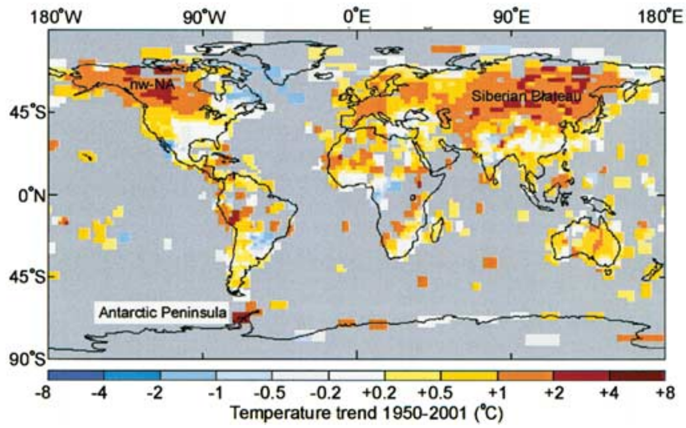

Figure 1.

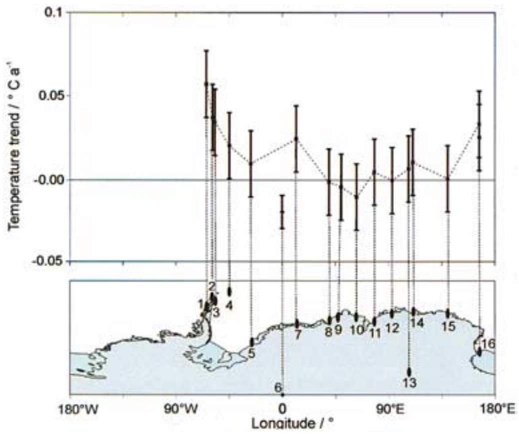

Figure 2.

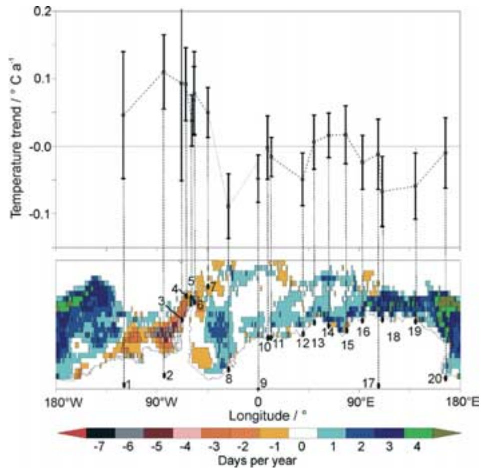

Figure 3.

warming which, in terms of geographical or climatic setting, are quite distinct. While unproven as yet, it is possible that each RRR warming may well have a similar underlying cause in the anthropogenic contribution to the greenhouse effect, but there is no reason to believe that amplification of the global mean change results from the same processes all three areas. Below, we show that the Antarctic Peninsula is a further example of RRR warming – one only hinted at in earlier assessments and, until now, not examined from this perspective.

3. Observed Climate Change in Antarctica

Surface cooling caused by increased concentrations of short-lived sulphate aerosols is known to have masked underlying climatic trends over several industrial areas (Mitchell and Johns, 1997). Similarly, heating of urban meteorological stations has long been suspected to mask the warming due to greenhouse gas emissions. Although the former can now be modelled (Mitchell and Johns, 1997) and the latter has been largely discounted (Peterson et al., 1999), temperature records from Antarctica are demonstrably free from these effects. So although few records from Antarctic station are longer than 50 years, the trends they show are a particularly important indicator of climate change.

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Figure 1. Trends in surface mean annual air temperature for the period 1950–2001, based on geographic smoothing of trends from individual stations. The image is a modified version of that presented by Hansen et al. (1999) and was drawn using data and tools available at http://www.giss.nasa.gov/ selecting surface temperature records from *GISS new analysis*. No ocean temperature data were included. The map was smoothed to 250 km. No data are available for areas shaded grey. Published Courtesy of NASA Goddard Institute for Space Studies.

Figure 2. Meridional variations of Antarctic temperature trends calculated for stations where records of 33 years or longer are available. Error bars are given at the 1-sigma (68%) level and location of stations is shown by dots in the sketch map. The stations are numbered as follows: 1. Faraday/Vernadsky, 2. Bellingshausen, 3. Esperanza, 4. Orcadas, 5. Halley, 6. Amundsen-Scott, 7. Novolazarevskaya, 8. Syowa, 9. Molodezhnaya, 10. Mawson, 11. Davis, 12. Mirny, 13. Vostok, 14. Casey, 15. Dumont D'Urville, 16. McMurdo and Scott. Note, while we normally require a single record to achieve two-sigma significance ($\sim$5%) significance to have credibility, here we show one-sigma uncertainty to allow inter-comparison of these station trends.

Figure 3. Meridional variations of Antarctic temperature trends calculated for the period of satellite observations of sea-ice duration. Comparison of the 1979–99 trends in the duration (in days per year) of ($>$15%) sea ice coverage after Parkinson (2002) are shown in the lower panel, and temperature trends for stations in the upper panel for the same period (Table II). Error bars are given at the 1-sigma (68%) level and location of stations is shown by dots in the sketch map. The stations are numbered as follows: 1. Byrd, 2. Siple, 3. Rothera, 4. Faraday/Vernadsky, 5. Bellingshausen, 6. Esperanza and Marambio, 7. Orcadas, 8. Halley, 9. Amundsen-Scott, 10. Neumayer, 11. Novolazarevskaya, 12. Syowa, 13. Molodezhnaya, 14. Mawson, 15. Davis, 16. Mirny, 17. Vostok, 18. Casey, 19. Dumont D'Urville, 20. Scott Base.

3.1. MEAN LONG-TERM TRENDS IN ANTARCTICA

The trend in mean annual temperatures from Antarctic stations has often been calculated, and invariably found to be significantly greater than global mean warming, this has led to a widespread belief that the ubiquitous 'polar amplification' of global warming, suggested by early GCM simulations of the response to increased carbon dioxide (e.g., Mitchell et al., 1990), is indeed noticeable in Antarctica.

Raper et al. (1984) used areally weighted trends from 16 stations and found a warming of 2.8 °C $(\text{century})^{-1}$ (1957–82). Jones (1995) supplemented station data with expedition reports to argue that Antarctic air temperatures in the late 20th century were at least 1 °C warmer that those prevailing during the first decade of the 20th century. Treating the Antarctic Peninsula stations as a single record, Jacka and Budd (1998) used a different set of 16 meteorological stations across Antarctica and found a mean trend of 1.2 ± 1.4 °C $(\text{century})^{-1}$ (1959–1996). Yet another analysis of 21 Antarctic stations, showed a warming trend of 1.2 ± 0.8 for a 45-year record beginning in the 1950s (Comiso, 2000). In a rather different study (see Section 6.2), van den Broeke (2000a) attempted to remove the effects of slow circulation changes which he believes cause regional modification of warming, to show a background warming trend (1957–1995) of 1.30 ± 0.38 °C $(\text{century})^{-1}$.

For reasons that have been discussed elsewhere (Turner et al., 2002), we do not consider the trends derived from post-1965 gridded data rather than original station records (Weller, 1998; Doran et al., 2002) to be reliable. In what follows, we will show that the cooling trend noted in those papers, is not reflected in the either the full station records or the records for the period 1977–1999.

We have reanalyzed Antarctic meteorological records of mean annual temperature, using updated methods of trend analysis (Table I, Figure 2). Linear trends were derived using a least-squares adjustment and the significance of these trends was determined using the t-test methodology outlined by Trenberth (1984). This methodology accounts for autocorrelation in the time-series by considering that the number of effectively independent observations is less than the actual number of observations and generally decreases the probable significance of the trends. In the calculation of temporal trend, the predictor variable, time, is not random, so the number of independent observations is computed using the residuals of the regression. Confidence intervals shown for the trends (see Section 8.3.7 of von Storch and Zwiers, 1999) are calculated at the one-sigma (31.7%) level with the degrees of freedom based on the number of effectively independent samples.

Although the data are sparse we believe that the satellite determined trends (Comiso, 2000) indicate a high level of spatial coherence in the trends over ranges of >1000 km. Such coherence is clear in the trends shown Figure 2, with neighbouring stations tending to show similar trends. The obvious problem with using this dataset to give a continental mean, is that most of the stations are coastal and there is a lack of data from the interior to give a reliable mean. Similarly there are no station records available in the sector 167° E – 065° W. Accepting these provisos

Table I

Trends in mean annual air temperature at meteorological stations in Antarctica. In selecting stations for inclusion in this analysis we reject records with fewer than 30 years of observations. Data were acquired from several sources. Records taken from British Antarctic Survey records are available at http://www.antarctica.ac.uk/climate/surfacetemps. Confidence limits on temperature trends are given at the 1-sigma level (∼31.7% significance), but significance level is also shown explicitly with 'not significant' implying anything greater than 10%

Station	Latitude/ °S	Longitude/ °E	Mean/ °C	Std dev/ °C	Trend/ °C (centurey)	Years	Sig.
Faraday/Vernadsky	65.25	–064.27	–4.0	1.6	5.7 ± 2.0	1951–2001 (51)	1%
Bellingshausen	62.20	–058.97	–2.4	0.8	3.7 ± 2.1	1969–2001 (33)	10%
Esperanza	63.4	–056.98	–5.3	1.2	3.4 ± 1.3	1946–48, 1953–78, 1980–2001 (51)	5%
Orcadas	60.75	–044.72	–4.0	1.2	2.0 ± 1.0	1904–91, 1993–2001 (97)	1%
Halley	75.58	–026.50	–18.6	1.1	0.9 ± 2.2	1957–2000 (44)	Not sig.
Novolazarevskaya	70.77	011.83	–10.3	0.6	2.4 ± 1.2	1962–2001 (40)	10%
Syowa	69.00	039.58	–10.6	0.8	–0.2 ± 1.7	1960–61, 1967–2001 (37)	Not sig.
Molodezhnaya	67.67	049.85	–11.0	0.6	–0.5 ± 1.5	1964–95, 1997–98 (34)	Not sig.
Mawson	67.60	062.87	–11.2	0.8	–1.1 ± 1.1	1955–2001 (47)	Not sig.
Davis	68.58	077.97	–10.2	0.9	0.4 ± 1.6	1958–63, 1970–2001 (38)	Not sig.
Mirny	66.55	093.02	–11.3	0.8	–0.1 ± 1.2	1956–2001 (46)	Not sig.
Vostok	78.50	106.90	–55.3	0.8	0.6 ± 1.7	1958–61, 1963–93, 1995, 1997–2001 (39)	Not sig.
Casey	66.28	110.53	–9.3	0.9	1.0 ± 1.8	1958–2001 (44)	Not sig.
Dumont D'Urville	66.67	140.02	–10.8	0.6	0.0 ± 1.3	1956–2001 (46)	Not sig.
McMurdo	77.85	166.66	–17.2	1.0	3.3 ± 2.3	1957–63, 1965–67, 1969–86, 1988, 1995–96 (31)	Not sig.
Scott Base	77.85	166.76	–19.9	1.0	2.5 ± 1.8	1958–93, 1995–2001 (43)	Not sig.
Amundsen-Scott	90.00	000.00	–49.5	0.6	–2.0 ± 1.0	1958–2001 (44)	10%

it is, however, valuable to consider whether these records can give any indication of a polar amplification of global mean warming.

An unweighted mean of the trends and 1-sigma uncertainty in those trends, determined for the 17 Antarctic stations (Table I) for which we have records longer than 33 years, but considering the Antarctic Peninsula stations (Faraday/Vernadsky-Orcadas) as a single record, suggests a mean warming for Antarctica of $0.8 \pm 1.6\,°C$ (century)$^{-1}$ (standard deviation, $1.6\,°C$ (century)$^{-1}$). However, this value is undoubtedly elevated by the inclusion of the Antarctic Peninsula stations, and removing these lowers the mean for the continental stations (Halley–Amundsen-Scott in Table I) to $0.6 \pm 1.5\,°C$ (century)$^{-1}$ un-weighted, $0.22\,°C$ (century)$^{-1}$ areally weighted using Thiessen polygons (c.f. Raper et al., 1984); and $0.49\,°C$ (century)$^{-1}$ weighted according to the length of the record.

Whichever weighting we choose, there is only weak evidence of significant overall warming in station data from continental Antarctica, and we find no evidence that this is significantly greater than the global mean warming during the

20th century (0.6 ± 0.2 °C, Houghton et al., 2001). Thus, we find no ubiquitous polar amplification of global warming in the Antarctic station data.

3.2. SPATIAL STRUCTURE IN LONG-TERM TRENDS IN ANTARCTICA

The mean warming for the Antarctic Peninsula stations (Faraday/Vernadsky–Orcadas, in Table I, 3.7 ± 1.6 °C (century)$^{-1}$ un-weighted; and 3.4 °C (century)$^{-1}$ weighted by length of record) is substantially greater than the continental mean, suggesting that a pronounced warming is detectable in this area. This difference is further emphasized by Figure 2, which shows a definite structure in the pattern of warming and cooling trends around Antarctica. While few of these records individually achieve 5% significance, the high spatial correlation in Figure 2, probably indicates that the pattern is significant. Thus, Figure 2 shows a probable warming in the sector from the west coast of the Antarctic Peninsula to Novolazarevskaya (065° W–011° E), no clear warming or cooling from Syowa to Dumont D'Urville (040° E–140° E), and probable warming around McMurdo and Scott bases (167° E). As has been noted elsewhere the record from Amundsen-Scott Base at South Pole shows a cooling, which we find to be significant at 10%. Given the sparsity of data, this could conceivably be representative of a considerable portion of the interior of the continent.

Figure 2 highlights that there are no long-term records in the sector, 167° E–065° W, an area bounded on both sides by probable areas of warming. As far as we can tell from these data, this sector may have suffered pronounced warming that has gone unrecorded.

3.3. CHANGES IN THE SATELLITE ERA (1979–1999)

While the sections above deal with the longest meteorological records (>33 years), there are more meteorological stations available with shorter records, and in recent years these data have been supplemented by satellite data that increase our confidence in interpolating between the sparse station data. We have considered the period 1979–1999 to be an era for which good quality, continuous satellite data are available.

The difference between the Antarctic Peninsula and the rest of the continent is, perhaps, more apparent during this period (Table II and Figure 3). While the Antarctic Peninsula has warmed 1979–1999, nine out of twelve of the stations from the rest of Antarctica, show cooling, although none achieve 5% significance. Comiso (2000) has noted this behaviour in station data through the period 1979–1998, but the results using our estimations of uncertainty and significance are presented in Table II and Figure 3. The cooling trend in station data over this period appears to be confirmed by several different signals in the satellite data. (1) Cooling in near-infrared satellite measurements of surface temperature (Comiso, 2000); (2) increases in sea-ice extent (Stammerjohn and Smith, 1997); (3) lengthening of

Table II

Trends in mean annual air temperature at meteorological stations relevant to the period of the satellite measurements of sea-ice duration. In selecting stations for inclusion in this analysis we rejected records with fewer than 18 years of observations. Data and analyses were drawn from British Antarctic Survey records (http://www.nbs.ac.uk/icd/gjma/temps.html), unless otherwise indicated. The Siple record is a combination of station and passive microwave data (Shuman and Stearns, 2001). Confidence limits on temperature trends are given at the 1-sigma level (~31.7% significance), but significance level is also shown explicitly with 'not significant' implying anything greater than 10%

Station	Latitude/ °S	Longitude/ °E	Mean/ °C	Std dev/ °C	Trend/ °C (century)$^{-1}$	Years	Sig.
Byrd	80.00	–120.00	–27.6	1.5	4.6 ± 9.4	1979–97 (19)	Not sig.
Siple	75.90	–083.92	–24.7	1.1	11.0 ± 5.5	1979–97 (19)	10%
Rothera	67.57	–068.13	–4.5	1.5	9.3 ± 14.4	1979–98, 2000–01 (22)	Not sig.
Faraday/Vernadsky	65.25	–064.27	–3.2	1.3	9.2 ± 5.4	1979–2001 (23)	Not sig.
Bellingshausen	62.20	–058.97	–2.2	0.9	3.8 ± 3.8	1979–2001 (23)	Not sig.
Esperanza	63.40	–056.98	–4.8	1.1	6.8 ± 5.0	1980–2001 (22)	Not sig.
Marambio	64.20	–056.70	–8.2	1.3	7.8 ± 6.2	1979–88, 1990–91, 1996–2001 (18)	Not sig.
Orcadas	60.75	–044.72	–4.0	1.2	5.0 ± 3.7	1979–91, 1993–2001 (22)	Not sig.
Halley	75.58	–026.50	–18.8	1.1	–8.0 ± 4.9	1979–2001 (23)	Not sig.
Neumayer	70.70	008.40	–15.9	0.7	–0.2 ± 4.7	1982–2001 (20)	Not sig.
Novolazarevskaya	70.77	011.83	–10.0	0.6	–1.6 ± 2.9	1979–2001 (23)	Not sig.
Syowa	69.00	039.58	–10.5	0.8	–4.9 ± 3.9	1979–2001 (23)	Not sig.
Molodezhnaya	67.67	049.85	–11.0	0.6	0.6 ± 4.0	1979–95, 1997–98 (19)	Not sig.
Mawson	67.60	062.87	–11.4	0.8	1.6 ± 3.3	1979–2001 (23)	Not sig.
Davis	68.58	077.97	–10.2	1.0	1.7 ± 4.3	1979–2001 (23)	Not sig.
Mirny	66.55	093.02	–11.3	0.8	–2.4 ± 4.0	1979–2001 (23)	Not sig.
Vostok	78.50	106.90	–55.2	0.9	–1.2 ± 5.2	1979–93, 1995, 1997–2001 (19)	Not sig.
Casey	66.28	110.53	–9.1	1.0	–6.7 ± 5.2	1979–2001 (23)	Not sig.
Dumont D'Urville	66.67	140.02	–10.7	0.7	–5.9 ± 4.9	1979–2001 (23)	Not sig.
Scott Base	77.85	166.76	–19.6	0.8	–1.0 ± 5.2	1979–93, 1995–2001 (22)	Not sig.
Amundsen-Scott	90.00	000.00	–49.6	0.8	–4.8 ± 3.5	1979–2001 (23)	Not sig.

sea-ice duration (Parkinson, 2002, and analyses shown in Figure 3); and (4) shortening of the summer melt period on the ice sheet (Torinesi et al., 2003). In each of these signals, however, the Antarctic Peninsula shows the opposite trend – consistent with continued warming. Together, these observations suggest that the Antarctic Peninsula is the only part of Antarctica with persistent warming throughout the period of satellite observation and this warming substantially different from the insignificant trends over most of the rest of the continent.

3.4. ANTARCTIC PENINSULA TRENDS

Topographically and climatically, the environment on the Antarctic Peninsula (Figure 4) is different to the rest of continental Antarctica – it is actually more similar to that in southern coastal Greenland. Most of the Antarctic Peninsula has a rugged alpine topography and summer air temperatures which exceed 0 °C at sea level. For that reason, surface melting is an important component in mass balance of the ice sheet, and the presence of melt-water and seasonally bare rock supports more terrestrial flora and fauna than elsewhere in Antarctica. Furthermore, the spine of the Antarctic Peninsula, an unbroken mountain chain 1400–2000 m above sea level, forms a distinct climatic barrier (Schwerdtfeger, 1984). The west and central regions have a maritime climate dominated by the Bellingshausen Sea, and the east coast has a continental climate dominated by the Weddell Sea (Martin and Peel, 1978). Due to these influences, the west coast of the Antarctic Peninsula is generally $\sim$7 °C warmer than at similar latitudes and elevations on the east coast (Reynolds, 1981; Morris and Vaughan, 1994).

Continuous meteorological records were begun on the Antarctic Peninsula during the Second World War. Prior to this, only a few short expedition reports are available and we believe that in view of the large interannual variability, those short datasets and inferences from them (e.g., Jones, 1990) have little significance. Table I shows that the long temperature records from the Antarctic Peninsula (Faraday, Esperanza and Bellingshausen) have trends an order of magnitude greater than global mean warming (0.6 ± 0.2 °C (century)$^{-1}$), each of which is individually significant at $<10\%$. With the exception of Rothera, warming in the shorter records at Marambio (Table II), and summer-only record from Fossil Bluff (Harangozo et al., 1997), have questionable significance, but do suggest that the RRR warming is present on the northern east coast and on the west coast as far south as Alexander Island. Finally, south of the Antarctic Peninsula, a 19-year mixed station and passive microwave record from Siple Station (Shuman and Stearns, 2001) shows a strong warming but with low significance (11 ± 5.5 °C (century)$^{-1}$), indicating that the southern boundary of the warming is not well-defined.

None of the meteorological records reveal when the warming on the Antarctic Peninsula began. A clue to this is, however, found in the record from Orcadas, South Orkney Islands. This station is several hundred kilometres from the Antarctic Peninsula but has continuous records for almost 100 years. Figure 5 shows that warming at Orcadas probably began in the 1930s. Annual temperatures at Orcadas do correlate with the Faraday record ($r^2 = 0.51$), confirming a degree of interannual similarity, and so it is arguable that warming on the Antarctic Peninsula may have begun at a similar time. An isotopic temperature record from Dyer Plateau offers confirmation of this interpretation (Section 5.1.2).

In addition to temperature trends, there has been a statistically significant increase in the number of reports of winter precipitation at Faraday (Turner et al., 1997) since 1956. This must be related to the change in the number of cyclones approaching from the Bellingshausen Sea from which this precipitation is derived (Turner et al., 1995), rather than simply an increase in precipitation due to increased atmospheric moisture content associated with warming; it points to changed circulation. These direct observations are probably more convincing than

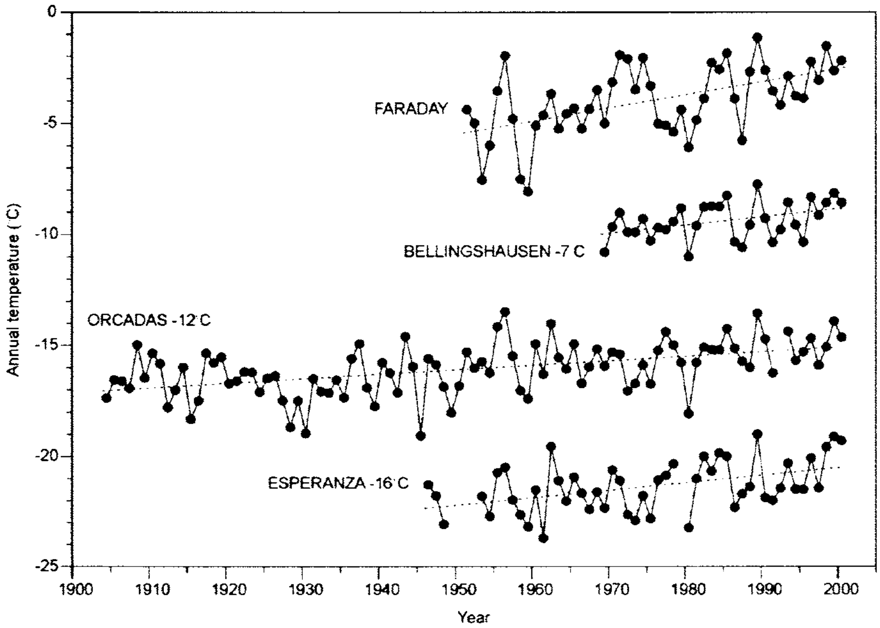

Figure 5. Meteorological records of mean annual air temperature from the Antarctic Peninsula. Dotted lines are trends given in Table II.

model reanalysis data that appear to indicate a decline in cyclone numbers to the west of the Antarctic Peninsula (Simmonds and Keay, 2000).

3.4.1. *Period of Trend*

An important test for the significance of trends in temperature data is insensitivity to the period of measurement. It has been suggested that the record of warming at Faraday would have been quite different if observations had not begun in the 1950s, and that the indicated warming is simply the result of step-changes in the 1970s. The trends calculated for subsets of this record (Table III) shows that this is not the case. Clearly, if we remove the very cold periods at the beginning and end of the 1950s the trend is reduced, but the sign of the trend is independent of the period chosen, although the significance level clearly declines for shorter periods.

The apparent cooling trend in the satellite determination of snow-surface temperature on Antarctic Peninsula temperatures over the last 20 years (see Figure 17d in Comiso, 2000) results from using only January and July monthly average data, and extension of this to all months gives a warming trend more in line with station data (Comiso, pers comm.).

3.4.2. *Seasonality of Trend*

Table IV confirms results from earlier studies (King, 1994; Stark, 1994) that the strongest warming at Faraday has occurred during the winter, but because of

Table III

Trends calculated for Faraday temperature record over different periods. Data from British Antarctic Survey records (http://www.nbs.ac.uk/icd/gjma/temps.html). Trends and significance were calculated using the same techniques as for Table I. Confidence limits on temperature trends are given at the 1-sigma level (~31.7% significance), but significance level is also shown explicitly with 'not significant' implying anything greater than 10%

Period	Trend (°C (century)$^{-1}$)	Significance
1951–2000	+5.6 ± 2.1	5%
1961–2000	+4.5 ± 2.5	10%
1951–1980	+4.8 ± 4.7	Not sig.
1961–1990	+4.6 ± 4.3	Not sig.
1971–2000	+3.6 ± 4.2	Not sig.

Table IV

Seasonality of trends in mean annual air temperatures recorded at Faraday, 1950–2001. Data from British Antarctic Survey records (http://www.nbs.ac.uk/icd/gjma/temps.html). Confidence limits on temperature trends are given at the 1-sigma level (~31.7% significance), but significance level is also shown explicitly with 'not significant' implying anything greater than 10%

Season	Mean and Std. dev. (°C)	Trend (°C (century)$^{-1}$)	Significance
Winter (JJA)	–8.6 ± 3.4	+11.0 ± 9	1%
Spring (SON)	–4.9 ± 1.5	+2.5 ± 4.4	Not sig.
Summer (DJF)	+0.3 ± 0.7	+2.4 ± 1.7	1%
Autumn (MAM)	–2.7 ± 1.9	+6.2 ± 6.0	5%

the large interannual variability of the winter temperatures the weaker summer warming is statistically more significant.

3.4.3. *Area of Trend*

The geographical extent of the RRR warming on the Antarctic Peninsula is difficult to determine because of the sparsity of the meteorological stations. The most southerly stations on the Antarctic Peninsula show the largest interannual variability and the largest decadal warming, both are smaller further north on the Antarctic Peninsula and in the South Shetland Islands. To the east, the record from Halley

Station is not significantly correlated on interannual timescales with the records from the east coast of the Antarctic Peninsula, and does not show significant warming. To the west, there are no stations in the Pacific sector.

4. Regional Impacts

Meteorological records provide the most direct evidence of temperature changes and are in that respect indispensable, but other environmental parameters affected by climate warming can indicate the geographical extent of the changes and improve confidence in spatial and temporal interpolation.

4.1. GLACIAL ICE

RRR warming on the Antarctic Peninsula has reportedly caused retreat of glaciers (e.g., Splettoesser, 1992; Morris and Mulvaney, 1995; Smith et al., 1999a) and reduction of snow cover (Fox and Cooper, 1998). Furthermore, where summer melting does not occur, increased precipitation appears to have caused some thickening of the ice sheet.

Passive microwave sensing satellites have been employed by several authors to measure the number of warm days per year on which the snow around Antarctica is wet enough to cause a high brightness temperature (Ridley, 1993; Zwally and Fiegles, 1994; Torinesi et al., 2003). Most recently, Torinesi et al. found that over the past 20 years, there was a trend towards fewer warm days around much of the Antarctic, in line with mean cooling over this period (Comiso, 2000). Only the Antarctic Peninsula showed an increase in the duration of the warm period over the past 20 years, at a rate of 0.5 ± 0.3 days year^{-1}, over a mean of 38.9 days melting per year.

A long-predicted consequence of warming on the Antarctic Peninsula, the retreat of ice shelves (Mercer, 1978), is now well underway (Vaughan and Doake, 1996), with retreat of seven ice shelves during the latter part of the 20th century (Doake and Vaughan, 1991; Ward, 1995; Rott et al., 1996; Cooper, 1997; Luchitta and Rosanova, 1998; Skvarca et al., 1998). Each of these ice shelves was close to the apparent limit of viability associated with the January 0 °C isotherm. Atmospheric warming appears to have driven the limit of viability further south with the resultant loss of more than 10 000 km^2 of ice shelves since the 1950s; ice shelves not close to the limit of viability have generally maintained their size (Vaughan and Doake, 1996). Most recently, Wilkins Ice Shelf and Larsen Ice Shelf – B (Scambos et al., 2000) have retreated and are now close to a configuration that is probably unstable, so that they may soon collapse catastrophically (Doake et al., 1998).

Although the loss of these ice shelves has little direct impact on wildlife, sea level, or anything but local climate, the pattern of recent retreat shows that ice shelves are sensitive to atmospheric temperature changes (Vaughan and Doake, 1996), and may well serve as important proxies of climatic conditions (see Section 5.2).

4.2. SEA ICE

The west coast of the Antarctic Peninsula is the only region of Antarctica where a strong correlation between sea-ice extent and near-surface air temperatures is observed (Weatherley et al., 1991); this could be related to the fact that the Antarctic Peninsula acts as a barrier to the eastward transport of ice from the Bellingshausen Sea (Enomoto and Ohmura, 1990; King, 1994). Cold winters along this coast are almost invariably associated with extensive winter sea ice in the Bellingshausen Sea (King and Harangozo, 1998). Such correlations become progressively weaker farther north and for months outside the winter period (King, 1994). Nonetheless, the effect is persistent and produces a significant auto-correlation in the mean annual air temperature for periods up to $\sim$3 years (King, 1994).

The short-term relationship between sea-ice extent and temperature is clear, but is there also evidence of long-term associations? Before the period of routine satellite measurements, only sporadic observations of sea ice from ships are available. These give some evidence for a Antarctic-wide retreat of sea ice (de la Mare, 1997), but show no geographic detail around the Antarctic Peninsula. Similarly, King and Harangozo (1998) found that sea ice in the Bellingshausen Sea during the 1950s probably lay outside the extremes of the post-1973 satellite data.

Several authors have investigated changes in sea ice around Antarctica for the period over which satellite data are available (Zwally et al., 1983; Parkinson, 1992; Jacobs and Comiso, 1993; Parkinson, 1995; Jacobs and Comiso, 1997; Comiso, 2000; Parkinson, 2002) and these do show a geographically-significant pattern. Perhaps, most relevantly, Parkinson (1994, 2002) considered changes in duration of sea-ice cover rather than changes in extent; this is probably the most appropriate parameter to compare with the temperature trends.

Figure 3 shows an analysis similar to that by Parkinson, comparing changes in the duration of ($>$15%) sea ice cover (1979–1999) around Antarctica to temperature trends from meteorological stations for the same period.

Broadly, there has been a reduction in the sea ice duration (1–2 days per year) throughout the Amundsen and Bellingshausen seas, as previously noted, no station data exist in this area. In detail, the zone of greatest negative trend in sea ice duration ($>$5 days per year) coincides with the two stations showing the strongest warming trend (Faraday and Rothera). From this we conclude that, in addition to the interannual correlation, there is a decadal relationship between changing sea ice and atmospheric temperature in this area. This is not surprising but implies that any mechanism that we propose as the cause of RRR warming must also entail a reduction of the sea ice.

4.3. LIFE

The impacts of RRR warming on the Antarctic Peninsula on the marine ecosystem and the terrestrial ecosystem have already been reviewed (Smith et al., 1999b; Convey, 2001) and so are only summarised here. RRR warming has caused significant changes in lake ecosystems (Quayle et al., 2002) and promoted expansions of populations of flowering plants (Fowbert and Lewis-Smith, 1994; Smith, 1994; Grobe et al., 1997).

Penguin distributions are undergoing fundamental reorganization due to climatic changes (Smith et al., 1999b). Adélie penguins, which require access to winter pack ice, appear to be declining around Faraday, while chinstrap penguins, which occur almost exclusively in open water, are increasing. Indeed, there is evidence that the rookeries being vacated by the Adélie penguins have been occupied continuously for ~644 years, and there is no evidence for the presence of chinstrap penguins earlier than 20–50 years BP. This change in the balance of populations has been attributed to RRR warming (Fraser et al., 1992), rather than the previously accepted hypothesis, that it resulted from the over-hunting of baleen whales and a resultant alteration in the abundance of food. If this is confirmed, the changes in penguin populations can be taken as evidence that RRR warming around Faraday is unusual in the context of the past six centuries (Smith et al., 1999b).

5. Centurial and Millennial Proxies from the Antarctic Peninsula

If the RRR warming on the Antarctic Peninsula were part of a natural mode of variability, we would expect similar changes to have occurred in the past. We have already noted that changing penguin populations seem to suggest that no similar event occurred in recent centuries, but this alone may be insufficient to convince us that RRR warming is exceptional. We now consider two further proxy records that strengthen the hypothesis.

5.1. THE ARCHIVE IN THE ICE

The accumulated layers of snow and ice in the Antarctic Peninsula ice sheet contain two important archives of temperature, the vertical profile of temperature, and the isotope composition. Both archives can be examined by drilling into the ice.

5.1.1. *Borehole Temperature*

The inversion of borehole temperature profiles to give time-series of surface temperatures (*borehole thermometry*) does not yield a unique record but does provide some indication of trends in surface temperature. It has been applied to both terrestrial (Huang et al., 2000) and ice-sheet boreholes (MacAyeal et al., 1991; Firestone, 1995).

Figure 4. Location map for the Antarctic Peninsula. Ice fronts are drawn approximately at their 1994 positions. Inset map shows the location of Amundsen-Scott Base (A-S), Novolazarevskaya (N), Scott Base (S), Bellingshausen Sea (B.S.), Amundsen Sea (A.S.), East Antarctica (E.A.) and West Antarctica (W.A.).

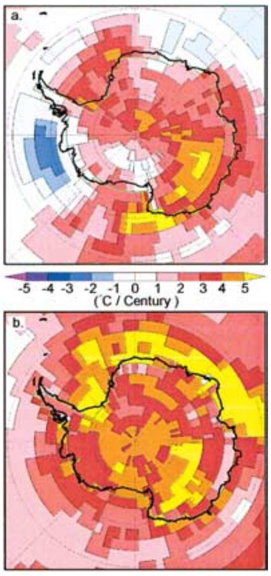

Figure 7. Changes in mean annual temperature 1.5 m above the surface of Antarctica and the Southern Ocean, predicted by the climate prediction model HadCM-3 driven by observed greenhouse gases concentrations. (a) for the period 1950–2000 and (b) for the period 2000–2050.

Two borehole temperature profiles have been obtained from the Antarctic Peninsula: Dyer Plateau, on the spine of the Peninsula at high elevation, and Dolleman Island on the East coast close to sea level. Both have near-surface temperature profiles that cannot be explained by steady climatic conditions, but which are consistent with a cooling in the late 19th and early 20th centuries, followed by a warming of around 2 °C since the mid-20th century (Nicholls and Paren, 1993). These temperature profiles thus corroborate the meteorological observations of warming over the last 50 years, and perhaps point to earlier cooling. Also, as we see below, they can provide an important check on the isotopic temperature record retrieved from the same holes; they do not, however, provide any evidence of whether the present warming is unique.

5.1.2. *Oxygen Isotopes*

Although factors other than temperature can also affect the isotopic composition of the ice (Jouzel and Merlivat, 1984), oxygen-isotope records are the favoured proxy for air temperature. We will refer to the temperature derived from oxygen-isotope records as the *isotopic temperature.* This proxy provides a higher-resolution record of climate than borehole thermometry and is usually calibrated using the modern spatial gradient of temperature and mean $\delta^{18}O$, and globally, isotopic temperature records show excellent correlation with measured meteorologically observed temperature (Rozanski et al., 1992). Indeed, isotopic temperature records from the interior of ice sheets are excellent proxies for long-term, hemispheric-mean temperatures (Petit et al., 1999). A complication lies in the fact that in the isotopic record, air-temperature is only sampled during precipitation events, and changes in the seasonality of precipitation or its source location will bias the isotopic temperature (Peel et al., 1988).

Century-long isotopic temperature records are available from four Antarctic Peninsula ice cores (Figure 6): Dyer Plateau (Thompson et al., 1994), James Ross Is. (Aristarain et al., 1990), Dolleman Is. (Peel et al., 1996) and Beethoven Peninsula (Mulvaney, pers. comm.). Three of the four sites show a slight rise in isotopic temperature over the last 50 years, beginning from apparently low values in the 1950s and 1960s, thus showing satisfactory agreement with the meteorological records. A similar rise is indicated in the isotope record from further south near Gomez Nunatak (74°01′ S 070°38′ W), although being only ∼38 years long (Peel et al., 1988), the Gomez record cannot indicate the longer significance of the RRR warming, and so is not discussed further here.

The isotopic temperature record from Dyer Plateau indicates ‘pronounced warming in which the last two decades have been the warmest in the last five centuries’ (Thompson et al., 1994). The mean isotopic temperature for the last 10 years is -20.5 ± 0.2 °C, compared to the mean for the last five centuries of -21.0 ± 0.05 °C. A ‘two-tailed T-test’ indicates a probability of <1% (T-value 4.05) that climate during last two decades has not changed from the period 1504–1959.

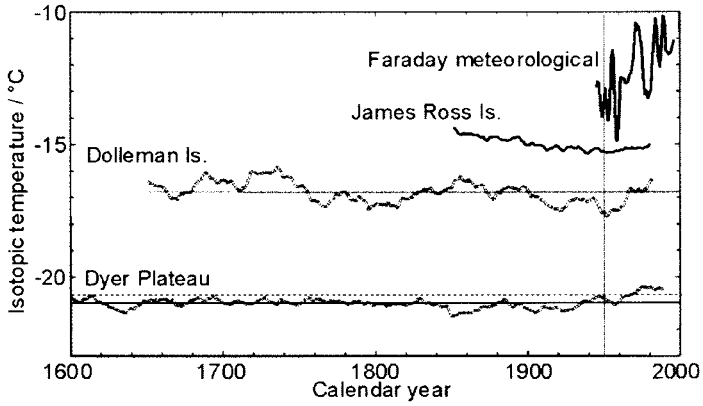

Figure 6. Temperature histories derived from ice core stable isotope records: James Ross Island 64°13′ S, 057°38′ W (Aristarain et al., 1986, 1990); Dolleman Island 70°35′ S, 060°55′ W (Peel et al., 1996); Dyer Plateau 70°40′ S, 064°52′ W (Thompson et al., 1994), together with the Faraday/Vernadsky meteorological record. Temperature is calculated from the measured δ^{18}O profile using a derived δ^{18}O: T gradient of 0.66‰/°C (Peel et al., 1988); each of the isotope records has been smoothed using a 21-year filter; the meteorological record is smoothed with a 5-year filter. The Dyer Plateau and Dolleman Is. records include the mean value (solid lines) and the Dyer Plateau record includes the 99% confidence intervals of the raw annual data in the period 1600–1950.

This record from Dyer Plateau does appear to indicate that RRR warming on the Antarctic Peninsula is exceptional over century timescales. However, it does need to be treated with caution. The mean annual isotopic temperature at Dyer Plateau (at an elevation of 398 m) is not well-correlated with the mean annual temperature at Faraday ($r^2 = 0.12$), indicating that it cannot be considered a simple proxy for west-coast temperature, and the magnitude of the warming (1 °C (century)$^{-1}$ over the last 50 years) is considerably less than that recorded in the meteorological records.

Isotopic temperature records from cores on the eastern coastal sites are more difficult to interpret. Even with 21-year smoothing, isotopic temperatures from both James Ross and Dolleman islands show high variability (Figure 6) in which the last 50 years are not exceptional. At face value, these isotopic temperatures indicate that the RRR warming may simply be part of normal climate variability for this area. However, we have several reasons to doubt that isotopic temperature records are a true reflection of atmospheric temperature. The fact that isotopic temperature from James Ross Is. shows no particular warming over the last 50 years is most surprising considering the position of this site between the meteorological stations Esperanza and Marambio, which experienced warming. Furthermore, when the isotopic temperature record from Dolleman Is. was used to drive a reconstruction of borehole temperature, it provided only a ‘rather poor fit’ to the measured temperature profile from the same borehole (Nicholls and Paren, 1993). A far better fit was obtained using synthesized records that included warming during the 20th century, casting doubt that the isotopic temperature from Dolleman Island is a good proxy for atmospheric temperature.

For these reasons and other involving analysis of deuterium excess as a marker of moisture source conditions, we follow earlier authors (Peel, 1992; Peel and Mulvaney, 1992; Nicholls and Paren, 1993), who concluded that decadal changes in isotopic temperature, on the east coast of the Antarctic Peninsula, are not a good record of air temperature, but are strongly modified by changing source regions for the moisture falling as precipitation and/or the seasonality of precipitation. In effect, we do not accept that the apparent oscillations of isotopic temperature from Dolleman and James Ross islands can be taken as evidence that RRR warming is simply part of a continuing cycle of climate changes, nor that it is necessarily limited to the west coast of the Antarctica Peninsula.

5.2. THE MARINE AND LAKE SEDIMENT ARCHIVE

Sparse but compelling lake sediment evidence suggest that during the late-Holocene (4700–2000 yr B.P) circum-Antarctic climate was warmer than more recent times (Ingolfsson et al., 1998), and with minor differences in timing, evidence for this *late-Holocene Climatic Optimum* (LHCO) also appears across the Southern Ocean (Labracherie et al., 1989; Ikehara et al., 1997) and into South America and Australia (Clapperton and Sugden, 1988; Kershaw and Nix, 1988). The best lake sediment records date the LHCO on the Antarctic Peninsula between 3800 and 2800 yr B.P. (Jones et al., 2000), and during this period climate may have been warmer than it is today. On the Antarctic Peninsula, the LHCO was followed by a period of Neoglacial cooling. A lack of reliable climate proxies covering this period has prevented us from confirming this interpretation, but our observation that ice shelves around the Antarctic Peninsula retreated as atmospheric temperature warmed to current levels, has allowed the development of a unique proxy over this timescale (Pudsey and Evans, 2001). This proxy relies on the distribution of ice shelves being controlled by atmospheric temperature, and while the process of this control is not entirely clear, there is wide agreement it is likely to exist and has caused the recent retreat of ice shelves (Rott et al., 1996; Vaughan and Doake, 1996; Scambos et al., 2000).

Until the ice shelf finally collapsed in the early-1990s, the pattern of deposition of ice-rafted debris in Prince Gustav Channel (Figure 4) was entirely constrained by the ice shelf. Sediment deposited in recent times (when the ice shelf filled the channel) was derived from either James Ross Island or the Antarctic Peninsula depending on position within the ice shelf. Core-top samples collected in 1999 reflected this constraint, but lower down mixed sediments showed periods when icebergs from both James Ross Island and the Antarctic Peninsula dropped ice-rafted debris across the entire channel. During these periods the ice shelf was certainly absent, implying that atmospheric temperature was probably similar to current levels. Carbon dating these events indicates that the ice shelf was absent throughout from 6000–7000 yr BP to 1900 yr BP, but was re-established after 1900 ka BP and has been present thereafter, until it disappeared in the early-1990s (Pudsey and Evans, 2001).

Given the resolution of samples in the sediment cores from Prince Gustav Channel, we are unlikely to resolve a period when the ice-shelf was absent for less than 100 years. However, given the measured velocity of ice on Larsen Ice Shelf A and Larsen Inlet before they retreated (Bindschadler et al., 1994), it is unlikely that these ice shelves could re-establish themselves in less than 200 years. Furthermore, we have no reason to believe that the ice shelf that occupied Prince Gustav Channel could re-establish itself more rapidly. A similar pattern was found in sediment cores from the area covered by Larsen Ice Shelf A until 1995 (Domack et al., 2001), although carbon-ages for these sediments are not yet available. Likewise, micro-palaeontological evidence from marine sediment cores collected in Lallemand Fjord on the east coast of the Antarctic Peninsula suggests a similar interpretation (Domack et al., 1995).

All these histories thus suggest that temperatures during the LCHO probably matched, or even exceeded, the present, confirming the palaeo-limnological evidence (Jones et al., 2000). In that respect, we interpret this to imply that the RRR warming may not have made current temperatures equal to the Holocene-maximum, but that recent warming is exceptional in the context of the past 1800 years (Pudsey and Evans, 2001). More importantly, we take this as further evidence that the RRR warming is not simply one in a succession of similar changes generated by a natural mode of regional climate variability, but results from regional climate change triggered by some unusual forcing.

6. Candidate Mechanisms

Bearing in mind the established connection between air temperature and sea-ice trends, and the uniqueness of the last 50 years in the previous 1800 years, we can now suggest mechanisms that may have initiated and sustained RRR warming on the Antarctic Peninsula. These suggestions are intended to show that despite a body of observations, there are still several plausible processes by which the global/hemispheric changes could be amplified to produce RRR warming. Furthermore, until we understand the process responsible, knowing whether or not anthropogenic greenhouse warming caused RRR warming, will not allow us to predict if it will continue, since we do not know if that process is close to saturation.

We can, however, easily discount one mechanism, the simple snow-cover-albedo feedback that has been described by Kellogg (1975), and which was probably responsible for promoting RRR warming on the Siberian Plateau (Serreze et al., 2000), from being significant on the Antarctic Peninsula – here there is only a small fraction of seasonally snow-free ground, too little to have a significant albedo effect.

6.1. CHANGED OCEANOGRAPHIC CIRCULATION

The continental shelf west of the Antarctic Peninsula is most unusual, in that relatively warm Circumpolar Deep Water (CDW) floods onto the continental shelf (Hofmann et al., 1996). Although this water lies deep in the water-column, tidal processes and the melting of glacial ice can bring it to the surface. Jacobs and Comiso (1997) suggested that changes in the properties of CDW or its rate of upwelling could influence sea-ice cover to the west of the Antarctic Peninsula. However, since only a few oceanographic measurements have been obtained in this area, no time series are available to test this hypothesis.

6.2. CHANGED ATMOSPHERIC CIRCULATION

Conditions on the Antarctic Peninsula are strongly influenced by the atmospheric circulation to the west over the Amundsen and Bellingshausen seas (ABS). A climatological centre of low pressure over the ABS drives a prevailing northwesterly flow onto the west coast of the Antarctic Peninsula, keeping it relatively mild. Marshall and King (1998) showed that extremely warm and extremely cold winters on the Antarctic Peninsula are associated with distinct circulation anomalies in the ABS and further afield. It is quite possible that RRR warming might also be driven by circulation changes.

Unfortunately, the ABS sector of Antarctica is largely devoid of meteorological data (see Section 3.1), and prior to the mid-1970s atmospheric analyses in this region were largely unconstrained and of dubious reliability (Hines et al., 2000). Only since the mid-1970s have the analyses have been constrained by satellite data and it is thus not possible to determine with a high degree of confidence whether there have been significant circulation changes in this region. Analysis of upper-level winds from radiosonde stations on the Antarctic Peninsula (Marshall, 2002b) show a significant increase in the westerly wind component between 1969 and 2000 but no significant increase in the northerly component that one might expect to be associated with warming. The increase in the frequency of winter precipitation events at Faraday over 1956–1993 reported by Turner et al. (1997) suggests a trend towards more cyclonic conditions, given that precipitation in this region is mostly derived from large-scale frontal systems. However, utilizing an automatic depression-tracking scheme, Simmonds and Keay (2000) detected a decline in Antarctic cyclone numbers in the ABS over the period 1958–1997 and, indeed found that this was one of the few coastal regions of Antarctica where cyclone frequency had not increased. However, this result may reflect problems with the early atmospheric analyses discussed above.

Several studies (e.g., Cullather et al., 1996; Trenberth and Caron, 2000) have indicated robust links between the atmospheric circulation in the ABS and the state of El Niño–Southern Oscillation. This suggests that the observed changes on the Peninsula may have their origin in changes in the tropical Pacific climate system. However, much remains to be understood about how such 'teleconnections' operate.

Another circulation change that has been advanced as an explanation of the rapid warming on the Antarctic Peninsula is a long-term change is the semi-annual oscillation (SAO), a twice-yearly contraction/expansion of the circum-Antarctic low-pressure belt. Van den Broeke (1998, 2000a,b) argued that cycles in the SAO (at periods of 12 and 35 years) may have influenced Antarctic Peninsula temperatures. However, the main changes observed in the SAO have occurred since the mid-1970s, while significant warming of the Peninsula took place between the 1950s and 1970s.

6.3. AIR-SEA-ICE FEEDBACK

While the first three mechanisms we have described would imply that the same process that drives atmospheric warming on the Antarctic Peninsula is driving changed duration of sea ice in the Bellingshausen Sea, it is possible that the connection is actually causal and is an expression of a regional feedback. In some ways this is similar to the snow-cover-albedo feedback but cannot be considered as simple as sea ice can be advected great distances. Some numerical models do appear to confirm that this feedback exists but not that it is a strong driver of regional climate change (Cai and Gordon, 1999).

Sea ice suppresses the transfer of heat from the ocean to the atmosphere during winter and increases regional albedo. Both effects lower air temperatures and favour further sea-ice production. The converse is also true and may explain the RRR warming with an initial impetus being supplied by local changes in the greenhouse effect, caused either by anthropogenic emissions or by increased water vapour. Indeed, there are several observations that support this mechanism quite strongly.

(a) Summer/winter significance – Winter temperatures along the west coast of the Antarctic Peninsula have much greater variability than summer temperatures, so that while, the warming trend is greater in the winter at all stations on the Antarctic Peninsula, the trend in summer temperatures has greater statistical significance. This is compatible with an underlying driving force present year-round, but with the magnitude of the amplification dependent on the presence or absence of winter sea-ice.

(b) Mid-troposphere warming – A composite series of mid-troposphere temperatures for the Antarctica Peninsula derived from radiosonde data shows warming at a pressure level of 850–300 hPa, $\sim$5 km above Faraday between 1954 and 1999 of $2.7 \pm 2.2\,^{\circ}\mathrm{C}\ (\mathrm{century})^{-1}$ (significant at 1% level) with no marked seasonality (Marshall et al., 2002). This warming is only 20% of the surface warming in winter but 15% greater than the summer surface warming. It is, however, similar to mid-tropospheric warming nearby at Halley and stations in East Antarctica (Marshall, 2002a). Finally, this also lies within the 5% confidence intervals of the mean trend

of six Antarctic stations for 850–300 hPa between 1958–98 (see Figure 3, Angell, 1999). In summary, there has been a year-round mid-tropospheric warming across Antarctica that approximately matches the summer surface warming on the Antarctic Peninsula, but is considerably less than the winter warming. This pattern fits the pattern of a winter-only amplification of a less pronounced year-round warming.

7. GCM-Representation of Rapid Regional Warming

Early *equilibrium response* experiments using General Circulation Model (GCM) investigations of increased greenhouse forcing showed strong warming over high-latitudes (e.g., Chen and Drake, 1986) which was termed a 'polar amplification' of climate change. These models lacked a representation of the deep ocean that could have transported heat away from those regions (Manabe and Stouffer, 1993), and more recent, *transient response* experiments with GCMs that include a deep ocean and realistic greenhouse and aerosol-forcing show less polar amplification. An ensemble of modern GCMs appears to agree that warming in the northern high-latitudes will be 'much greater' that the global mean, although warming in southern high-latitudes was only 'greater' than the mean (Giorgi et al., 2001).

Considering the means given in Section 3.1, we find that treating the Antarctic Peninsula stations as a single record, or considering them separately, the warming of continental Antarctica over the last 50 years is not significantly different from the global mean. Although we argue here that the Antarctic Peninsula is undergoing a RRR warming that is dissimilar to that seen over the rest of the continent; we find no evidence in the meteorological data of a ubiquitous polar amplification over Antarctica.

Attempts to identify the 50-year RRR warming on the Antarctic Peninsula, in simulations using the Hadley Centre for Climate Prediction and Research model, HadCM2 (Connolley and O'Farrell, 1998) were unsuccessful. Although this model crudely resolves the Antarctic Peninsula, when the model was forced using observed levels of CO_2 for the past 50 years, the temperature trends generated over the Antarctic Peninsula were much lower and had entirely the wrong geographical pattern. Furthermore, the natural variability predicted by the model was too small to explain the trends as a random fluctuation in interannual noise.

Since that study, an improved model (HadCM3) has been developed (Gordon et al., 2000). This uses improved resolution of the ocean, better physical parameterization, and does not rely on artificial flux corrections to maintain the ocean energy budget. The warming trend for the Antarctic Peninsula predicted by HadCM3, driven by an ensemble of CO_2 histories (Figure 7), is now technically within the 5% significance-range of trends determined at Faraday. However, the modelled trend is really only apparent if we make a careful selection of the time period and the season. In addition, the geographical pattern of warming produced by HadCM3 over the past 50 years is very different from that observed. The centre of the warming is in the Ross Sea and is pronounced in East Antarctica. The nearest warming to the Antarctic Peninsula is centered in the Weddell Sea and a cooling is apparent in the Bellingshausen Sea (Figure 7). Although, there is little meteorological data from the Weddell Sea, sea-ice duration has not decreased and does not suggest a recent warming here (Parkinson, 2002). Also the cooling in the Bellingshausen Sea suggested by the model is contrary to sea ice observations. This may be a result of a poor representation of sea ice distribution in the control run for HadCM3 giving a poor starting point from which to measure changes, but nevertheless this highlights that this GCM does not reproduce the RRR warming in a realistic way.

Although we present output from only one GCM, this is a state-of-the-art example and other GCMs have entirely comparable difficulties. Many GCM simulations 'that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century' (Houghton et al., 2001), they do not reproduce the profound regional changes such as those on the Antarctic Peninsula. Their spatial resolution is a probable cause of this mismatch, but it is also likely that no models yet have adequate representations of the regionally specific physics (e.g., sea ice production and transport) that will allow reliable regional predictions.

8. Conclusions

Many studies have demonstrated the great complexity in global trends in atmospheric temperature over the past 1000 years. We have identified three areas of recent rapid regional (RRR) warming, which all occur at high latitudes and in which warming has been several times the global mean. These areas of RRR warming are in different climatic regimes and there is no reason to suppose that they have a common origin. To understand what causes each RRR warming we will need to understand the climate processes that have caused them at a regional level. As a step towards this we have presented a detailed discussion of the RRR warming on the Antarctic Peninsula.

Station records show that the Antarctic Peninsula has warmed at $3.7 \pm 1.6\,^{\circ}$C (century)$^{-1}$, several times the rate of *global warming* and quite different to most of the other station records from the Antarctic continent. In fact, when considering the long-term station records from Antarctica, we find no evidence for a 'polar amplification' of climate change elsewhere in Antarctica. Rather, we see a regionally variable pattern, with an underlying warming not significantly different to the global mean.

The analyses highlight the lack of any long-term station records in the Amundsen Sea sector of Antarctica, and absence of direct evidence for warming in this area. However, sea-ice duration has declined around this portion of coast during the last three decades suggesting that there may well be changes in this area.

RRR warming on the Antarctic Peninsula is having documented impacts on, terrestrial flora, seasonal snow cover, lake ecology, penguin distribution, ice-shelf distribution, glacier thickness and sea-ice duration. We have argued that three climate proxies, oxygen-isotope records from ice cores, marine sediments recording the presence and absence ice shelves, and the occupation of penguin rookeries, all seem to suggest that no similar warming has occurred for at least 1800 years, making the RRR warming exceptional in this period.

If the RRR warming on the Antarctic Peninsula is exceptional over this timescale, it is unlikely that the present changes can be explained simply as a mode of natural variability; rather we must consider what outside driver caused the change. Comparison of the magnitude of the warming, with a recent assessment of the change in sea-ice duration clearly indicates that warming is linked to sea-ice conditions, but here cause and effect have not yet been identified. We believe that any combination of three distinct candidate-mechanisms could have caused the RRR warming; changing oceanographic circulation (e.g., an intrusion of CDW onto the continental shelf), changing atmospheric circulation (perhaps linked to ENSO, Trenberth and Caron, 2000), or local greenhouse warming amplified by sea-ice processes. The last of these appears to be consistent with mid-tropospheric temperatures trends, the seasonality of surface trends and the exact positioning of the greatest warming signal. However, until we understand which candidate-mechanism is responsible, we cannot predict the likelihood that the RRR warming will continue.

Among the local impacts of continued RRR warming would be, continued retreat of ice shelves, retreat of low-altitude glaciers, increased seasonality in some snowfields. Biological habitats will continue to undergo changes in extent, although it is unlikely that any particular species would be seriously threatened (Convey, 2001). Similarly, there would probably be few global impacts resulting from changes on the Antarctic Peninsula (Anisimov et al., 2001) – some contribution to sea level change is expected, although its sign is unpredictable at present.

These profound changes in a small region of Antarctica demonstrate that the future of regional climate change will probably be one dominated by regional triggers and feedback processes. The 50-year rapid warming may, or may not, have its root cause in global anthropogenic climate change, but whether or not it does is relatively unimportant from the point of view of impact assessment and adaptation. The same may be true for more populated areas of the world. In which case, *regional climate changes* will most probably have a more profound impact on human activities than *global mean warming*.

While the IPCC has discussed the impacts of climate change at continental scales (Watson et al., 1998) there are many bodies engaged in similar efforts at national (regional) scales (e.g., Nishioka and Harasawa, 1998; McKenzie Hedger et al., 2000; National Synthesis Team, 2000), evidence that good predictions of regional climate change are a pressing requirement for the purposes of national impact assessment and planning adaptation policies. However, for such studies to be based on realistic predictions, we must achieve competency in predicting regional climate changes. This study has shown that on the Antarctic Peninsula, our observations are currently inadequate to reproduce or understand the underlying processes responsible for RRR warming. The warming may be beginning to become visible in the trends produced by the best GCM simulations, but it is not yet clear that the match is not fortuitous. Clearly, understanding the cause of recent regional anomalies of climate is a high priority, as is reproducing them in climate models. The undoubted advances of recent years in reproducing global warming are impressive, but these models are not yet ready to provide us with a reliable basis for planning national adaptation and mitigation, and should be improved with utmost haste.

Acknowledgements

We wish to acknowledge the contribution made by all Antarctic meteorological observers collecting data under difficult circumstances who have contributed to the records analysed here, and to NASA GISS for making many data easily available. We acknowledge the Hadley Centre for free access to output from HadCM3. Alan Rodger and Eric W. Wolff have made valuable comments on the manuscript.

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(Received 8 April 2002; in revised form 22 January 2003)